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(CEMAC)*

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Abstract

Manufacturing capacity for lithium-ion batteries (LIBs)—which power many consumer electronics and are increasingly used to power electric vehicles—is heavily concentrated in east Asia. Currently, China, Japan, and Korea collectively host 88% of all LIB cell and 79% of automotive LIB cell manufacturing capacity. Mature supply chains and strong cumulative production experience suggest that most LIB cell production will remain concentrated in Asia. However, other regions—including North America—could be competitive in the growing automotive LIB cell market under certain conditions. To illuminate the factors that drive regional competitiveness in automotive LIB cell production, this study models cell manufacturing cost and minimum sustainable price, and examines development of LIB supply chains and current LIB market conditions. Modeled costs are for large format, 20-Ah stacked pouch cells with lithium-nickel-manganese-cobalt-oxide (NMC) cathodes and graphite anodes suitable for automotive application. Production volume is assumed to be at commercial scale, 600 MWh per year.

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Introduction

LIB Cell Manufacturing Capacity and Locations

In 2015, the world's total LIB cell manufacturing capacity was primarily located in China, Japan, and Korea. Together, these countries hosted 88% of total global LIB cell manufacturing capacity for all end-use applications.¹ These countries were also home to a significant share of LIB-specific materials manufacturing capacity, including that for cathodes (85% of global capacity), anodes (97%), separators (84%), and electrolytes (64%). This concentration of cell manufacturing capacity and upstream supply chains contributes to LIB industrial clusters in each of these countries. Note that these numbers do not include the Tesla “gigafactory”, which at the announced 35 GWh manufacturing capacity will significantly alter the global manufacturing landscape (Tesla 2016).

The LIB manufacturing clusters in China, Japan, and Korea are a result of longstanding public and private investments in the LIB sector. For instance, Japan's concentration of LIB cell and upstream processed materials suppliers grew from sustained investments in LIB technology by consumer electronics companies in the 1990s. These companies saw promise in LIB technology for the impact that the higher energy densities enabled could have on the performance of their core portable electronic device businesses. The Japanese government bolstered private sector investments with R&D funding and low-cost capital to establish manufacturing plants (Brodd 2012). Korea and China followed Japan's lead in investing in LIB cell and pack production for consumer electronics, and have created their own LIB production clusters. Korea's LIB cluster is a result of government and industry efforts, started in the 2000s, to build up this portion of the supply chain within Korea (Venkataraman and Gartner 2011; Alexander and Gartner 2013). China, too, has fortified its LIB cluster development through various government R&D programs, tax incentives, investment incentives (Patil 2008), domestic content requirements, and export restraints (Haley 2012; Stewart 2012). While Korean and Chinese cell manufacturers initially relied heavily on Japanese suppliers, their national efforts to build LIB clusters have resulted in less dependence on Japanese suppliers (Venkataraman and Gartner 2011; Alexander and Gartner 2013), and may contribute to the advantageous pricing observed in these regions for key materials for fully scaled, co-located Korean and Chinese cell producers (Wessner and Wolff 2012).

¹ Capacities include facilities that are fully commissioned, partially commissioned, and under construction.

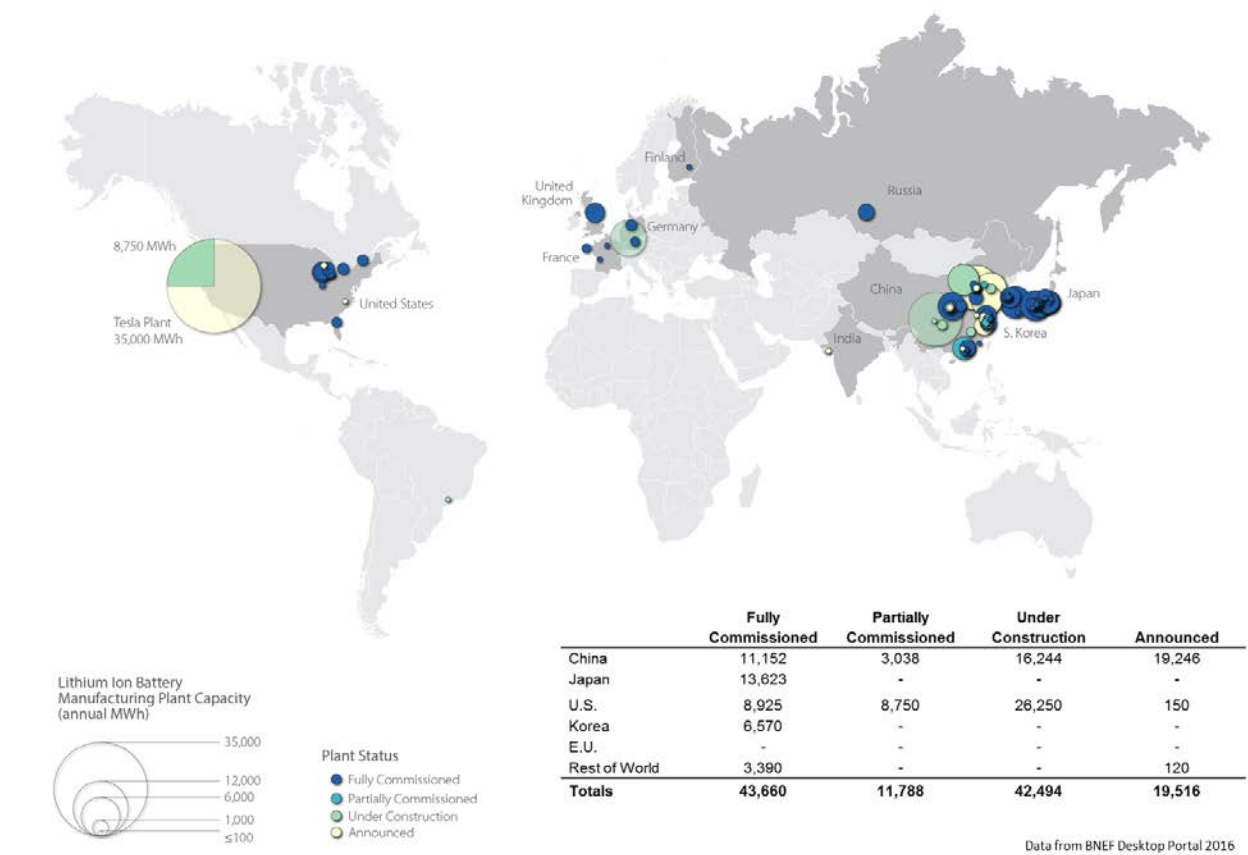


Figure 1. Global automotive LIB manufacturing capacity

Relative to these Asian manufacturers, the United States is home to an immature LIB supply chain, and most U.S. cell and battery plants are relatively new, though notably some are owned by firms with experience in battery production (e.g., LG Chem). However, the United States is a leading nation in automotive LIB production capacity, and currently hosts 20% of global automotive LIB cell capacity, surpassing the auto-specific share of early-mover Korea. Nearly all U.S.-based LIB capacity is targeted at serving the emerging automotive market. Global capacities by country for auto-specific LIB cell production are presented in Figure 1.

Projected Automotive LIB Demand Growth

We estimate automotive LIB demand will grow at a 36% compound annual growth rate (CAGR) from 2015-2020 (using data from BNEF Desktop Portal 2016; Technavio Insights 2015; Shepard and Jerram 2015; Behl; 2015; IEA 2015; Davis et al. 2015), from 11 GWh in 2015 to 54 GWh in 2020 (Figure 3). The projected growth is driven by demand for electric vehicles including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) (collectively referred to as “xEVs”). Demand for xEVs in all geographic markets is sensitive to several key drivers, namely governmental requirements for fuel economy and/or emissions, governmental demand- and supply-side subsidies, the cost of xEV drivetrain technology, charging infrastructure, consumer preference, and the prices of gasoline and diesel. Electric vehicles of all types currently comprise only a small portion of the total light duty

vehicle (LDV) market. Furthermore, many HEVs, which constitute a large portion of the xEV market, utilize nickel metal hydride (NiMH) batteries, not LIB (though this is beginning to change). However, xEV sales are expected to grow at a 44% CAGR through 2020, as presented in Figure 2, whereas total LDV sales are forecast to grow at a 1.4% CAGR over the same time period. Note, while 2015 is labeled as a forecast year, we include one actual data point for this year in our average, while all other sources reflect forecasts.

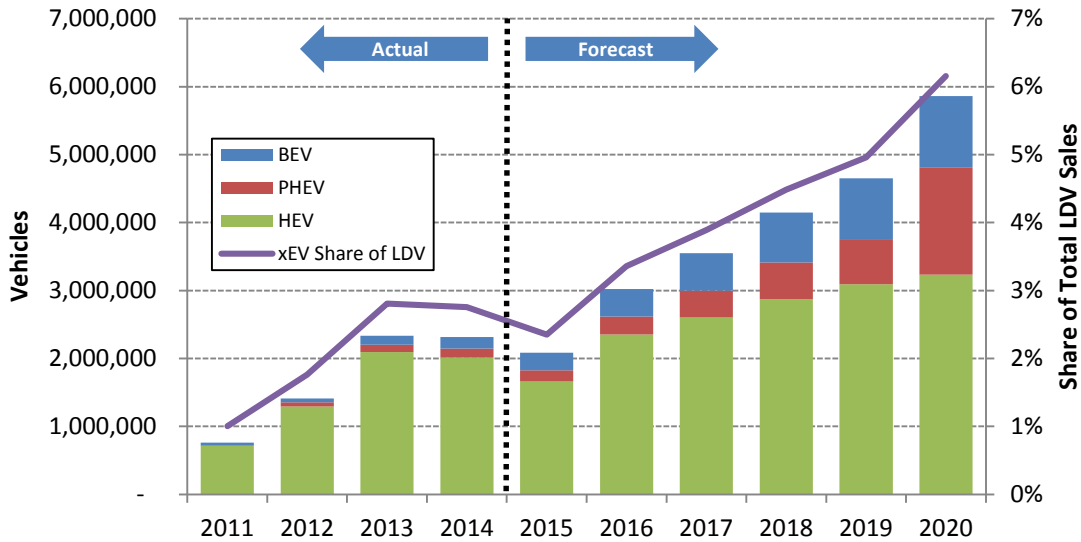


Figure 2. Global xEV sales and share of total LDV sales

Source: Average of data from BNEF Desktop Portal 2016; Technavio Insights 2015; Shepard and Jerram 2015; Behl 2015; Alexander and Gartner 2014; and IEA 2015

Initial overly optimistic assumptions regarding xEV demand (and BEV/PHEV demand, particularly) have contributed to an overbuild of large format LIB cell production capacity targeted at vehicle markets (Figure 3). Global average utilization was estimated at 22% at the beginning of 2014, and is expected to reach 40% in 2016. While overcapacity conditions are improving, it is still likely exerting negative price pressures upon industry participants. If global capacity remains at 2016 levels, capacity and demand will come into better balance in the coming years, with the need for new capacity arising in 2019-2020.

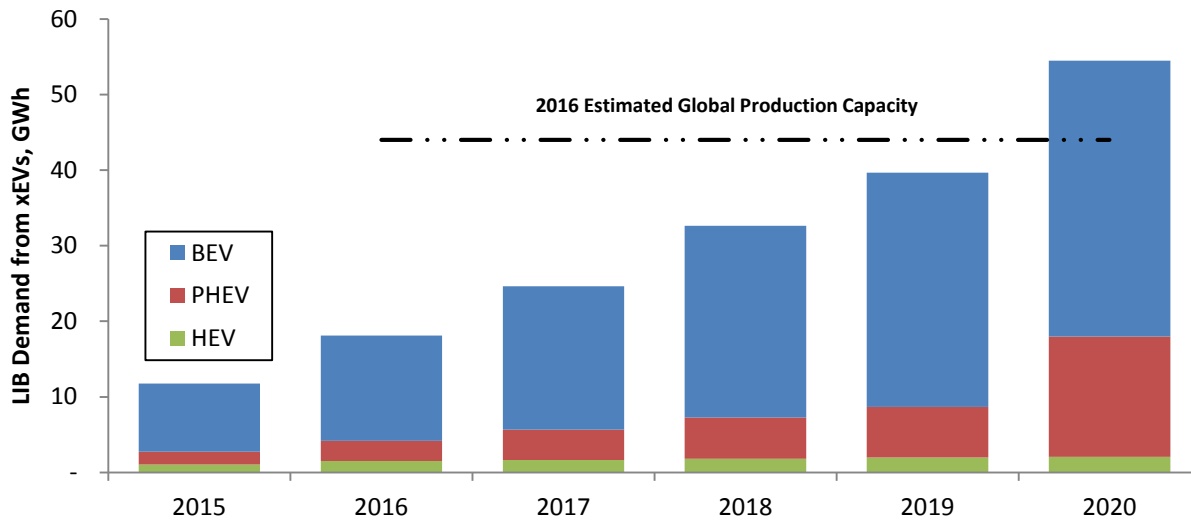


Figure 3. Estimated xEV LIB demand and global automotive LIB manufacturing capacity

Source: Data from BNEF Desktop Portal 2016; Technavio Insights 2015; Shepard and Jerram 2015; Behl 2015; Davis et al. 2015; and IEA 2015

However, the data in Figure 1 suggests that capacity is likely to continue growing, and overcapacity conditions may persist. Nearly 55 GWh of capacity is currently either partially commissioned or under construction, and a further 20 GWh of capacity has been announced.

Methods

The NREL cost model is based upon a detailed technical LIB cell production process model, enabling a bottom-up accounting of the total costs that a manufacturer incurs in the high-volume production of large format automotive LIB cells. The model quantifies performance parameters for each process step, including material consumption, energy consumption, labor requirements, equipment utilization, throughput, and yield. By then assigning estimates for all capital, fixed, and variable costs associated with each process step, an integrated techno-economic model for LIB cell production is created. Finally, the model accounts for typical operating, research and development, and tax expenses incurred by an LIB manufacturing firm. This detailed technical and cost information is used to create an integrated *pro forma* financial model, from which a minimum sustainable price (MSP) can be determined using discounted cash flow methods (Powell 2013; Goodrich 2013). Conceptually, the MSP is the selling price that enables a manufacturer to realize an internal rate of return (IRR) equivalent to their weighted average cost of capital (WACC). This is a theoretical construct that attempts to represent a long-term price required for healthy, sustainable operations assuming the current WACC for a set of public firms engaged in the battery business. It is important to note that market forces dictate actual selling prices, which may not align with computed MSPs.

The model assumes that a new LIB cell manufacturing facility is built and operated throughout its useful life by a single firm. Modeled costs are for large format, 20-Ah stacked pouch cells with lithium-nickel-manganese-cobalt-oxide (NMC) cathodes and graphite anodes. Production volume is assumed to be 8.3 million cells (600 MWh) per year. A simplified process flow of the manufacturing process is shown in Figure 4.²

² Operational parameters and capital equipment costs derived from equipment manufacturers' information, interviews, and NREL estimates.

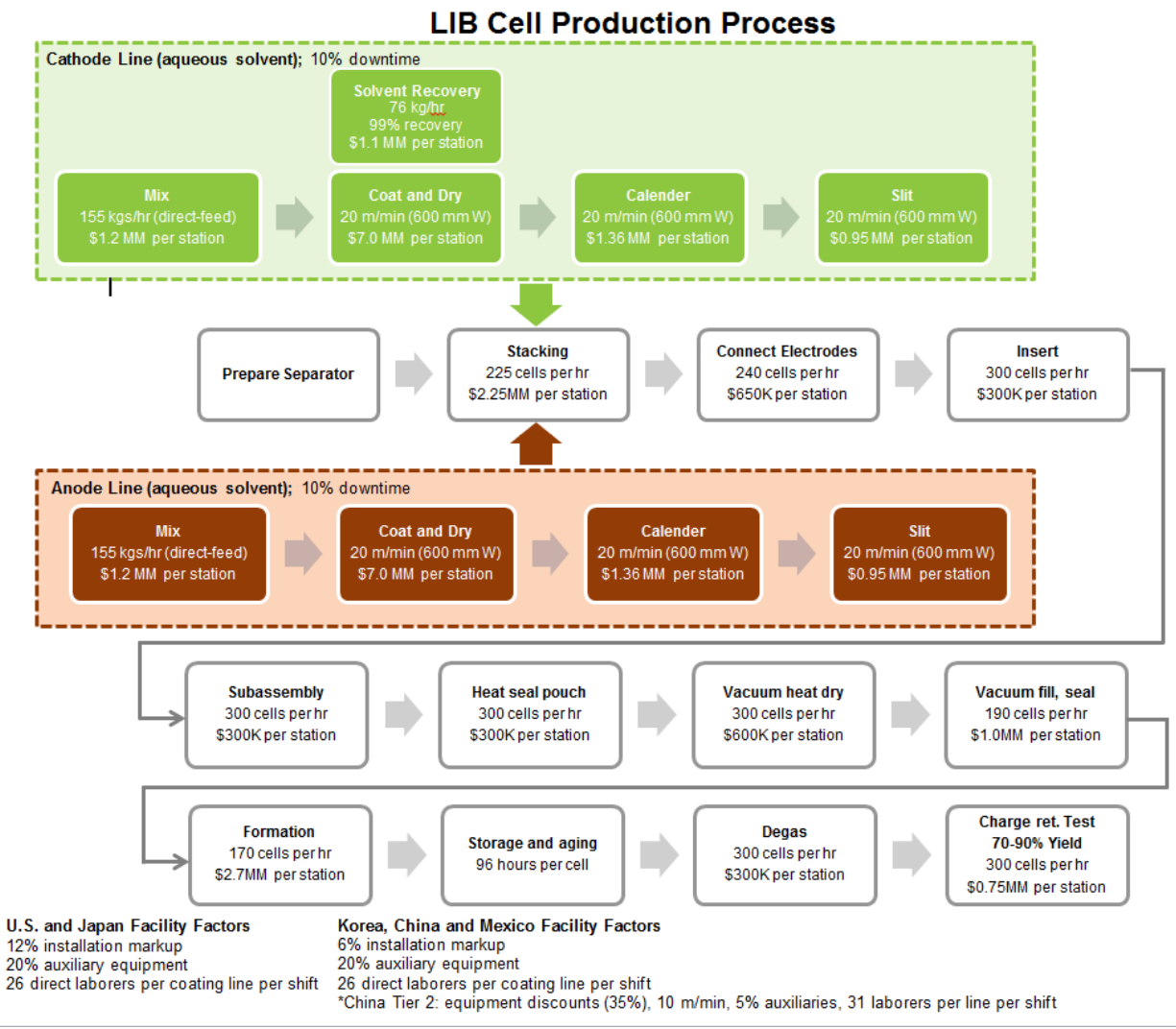


Figure 4. LIB manufacturing process flow

Country Scenarios Modeled

Representative scenarios are developed with the intent of benchmarking the performance of actual firms operating in the countries studied, while future scenarios are developed to understand the effects of various drivers upon the potential competitiveness of different country and firm scenarios and the risks and opportunities these may present. In modeling country scenarios, we assume that values for certain parameters are either wholly or in part country-specific. Country-specific values are utilized for parameters such as labor rates, energy costs, facilities costs, costs of capital, and 25 additional inputs (key scenario assumptions are included in the Appendix A. Eight country scenarios are developed as described in Table 1.

Table 1. Country Scenarios Modeled

Scenario	Description	Company Domicile / Manufacturing Location
U.S. Startup ¹	Relatively new market entrant with focus on technology R&D through commercialization.	U.S. / U.S.
U.S. Transplant (Korea) ¹	U.S. manufacturing facility owned by a Korean corporate parent with experience in automotive and consumer electronics LIB.	Korea / U.S.
Japan ¹	Japanese firm with experience in automotive and consumer electronics LIB.	Japan / Japan
Korea ¹	Korean firm with experience in automotive and consumer electronics LIB.	Korea / Korea
China Tier 1 ¹	Chinese firm with experience in automotive and consumer electronics LIB.	China / China
China Tier 2 ¹	Chinese firm with experience in automotive and consumer electronics LIB. Firm employs less automated processes and slightly lower quality materials.	China / China
Mexico Transplant (Japan) ²	Mexican manufacturing facility owned by a Japanese corporate parent with experience in automotive and consumer electronics LIB. Combines Mexico region advantages with incumbent firm advantages.	Japan / Mexico
U.S. Future ²	U.S. firm partnering with more experienced firms to produce LIBs in the U.S. Combines U.S. region advantages with incumbent firm advantages.	U.S. / U.S.
¹ Representative scenario ² Future scenario. Note the Mexico Transplant (Japan) scenario is developed solely to present what may be possible under certain conditions; there are no known existing or planned LIB production facilities in Mexico as of this writing.		

Key Model Inputs

Labor Costs

Labor rates for each country scenario are estimated using international wage data from the U.S. Bureau of Labor Statistics (BLS), with the exception of rates for China. BLS rates for China were as of 2012, but many regions within China have witnessed a rapid rise in labor rates for the past few years (Wall Street Journal 2014). Because of this growth, labor rates in China are approximately equal to—or possibly in excess of—those in Mexico today (“Mexico vs. China” 2014; “UPDATE 1” 2013; Coy 2013). The model makes the simplifying assumption of equivalent labor rates for China and Mexico.

Materials Costs

The model arrives at material costs for each scenario by applying a two-level breakdown of materials costs. First, general material prices are assumed to be lower for high-volume incumbent manufacturers based on purchasing volumes. All scenarios assume this volume discount for materials except the *U.S. Startup* scenario. Second, for certain materials (most critically cathode active materials) additional local production discounts are applied in the *Korea* and *China* scenarios, as it appears that particularly close supplier relationships, encouraged by overall national industry development objectives, could result in additional material cost advantage to LIB cell manufacturers located in these countries (Wessner and Wolff 2012). Further, in China, there are explicit domestic content requirements and export restraints that may contribute to lower materials costs for Chinese cell producers (Haley 2012; Stewart et al. 2012).

For example, the *Mexico* scenario assumes an experienced Japanese corporate parent, and thus volume pricing discounts are applied to the *Mexico* scenario. However, the location-based material discount is not applied to this case, as the additional discount is assumed to be applicable only to manufacturers co-located with the materials suppliers in Korean or Chinese LIB industrial clusters.

Equipment Costs and Performance

The model incorporates all costs associated with each production step including installation of auxiliary equipment costs. Because installation costs are driven by labor rates, the effects of differences in labor rates across regions are compounded. Some process steps may require multiple stations, and equipment requirements per process steps vary depending on the annual production (number of cells) volume being modeled. Equipment performance parameters such as speed, throughput, labor requirements, material consumption, etc. are incorporated in the model.

Weighted-Average Cost of Capital

MSPs are derived by incorporating the modeled capital and operating costs into a discounted cash flow analysis, where cell sales at the MSP must generate sufficient return to cover the assumed cost of capital. Regional WACCs were estimated using a set of comparable firms domiciled and publicly traded on exchanges within each of the countries of interest. For the transplant cases (Korean transplant in the United States, Japanese transplant in Mexico), the cost of capital assumed was based upon comparable companies domiciled in the parent company's home country. The model appends an additional country risk premium (or discount) based upon the credit default swap spreads against sovereign bonds between the parent company's country of domicile and the manufacturing facility location.

Yield and Utilization

The cost model also assumes 85% utilization and 80% total yield across all country scenarios except in the *China Tier 2* scenario. A 90% utilization and 70% total yield are assumed for the *China Tier 2* scenario due to lower automation levels modeled in that scenario. This also impacts *China Tier 2* equipment pricing (slightly lower due to less sophisticated equipment) and labor costs (slightly higher due to less automated processes) when compared to *China Tier 1*.

Results and Discussion

Modeled Cost

The data and assumptions used to model all costs and MSPs presented here were collected in 2014 and early 2015; as such, the results are intended to be representative of the conditions in 2014 and early 2015.

Materials represent the largest share of total cell cost—74% on average across all scenarios modeled. Of this, four materials represent 75% of total material costs: cathode active materials, here modeled as NMC (32%), separator (18%); electrolyte (16%); and anode active materials, here modeled as graphite (11%). Other materials each comprise less than 10% of the total materials cost. The average modeled material cost breakdown across all regions is shown in Figure 5.

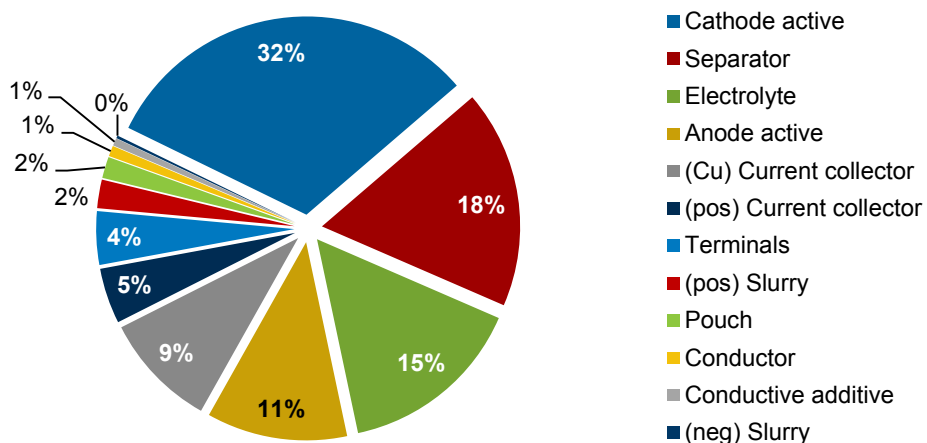


Figure 5. Average modeled material cost breakdown

Cell cost breakdowns by country scenario are presented in Figure 6. By comparing the highest and lowest total cost scenarios (*U.S. Startup* vs. *China Tier 1*), it appears that the differences in materials (\$202 vs. \$168) and labor (\$28 vs. \$2) costs drive the majority of the difference between the scenarios.

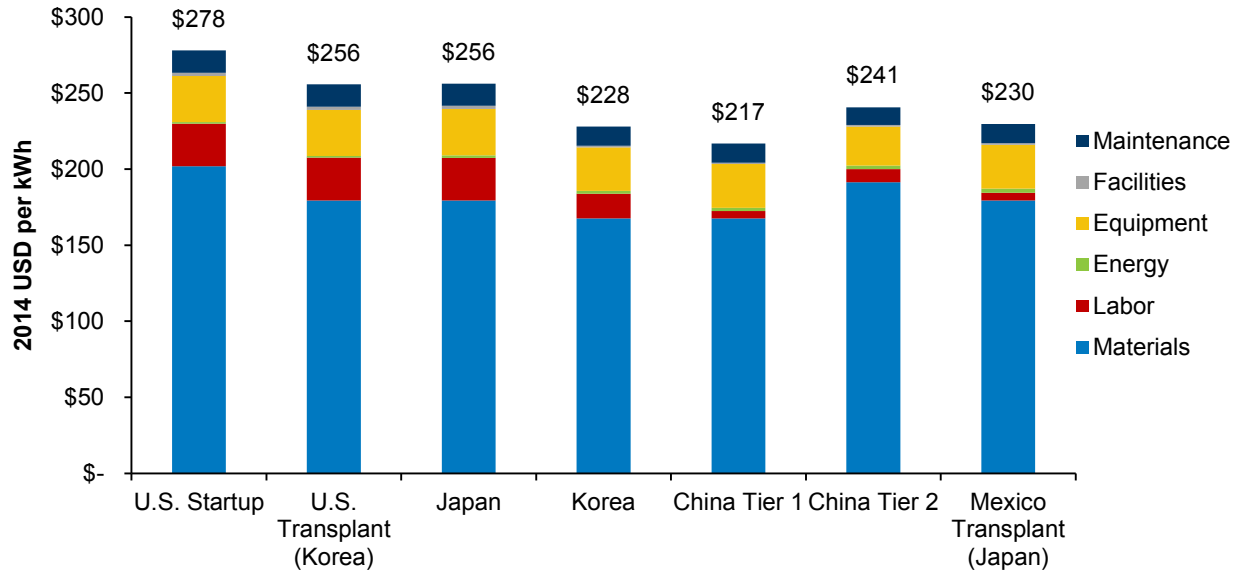


Figure 6. Modeled cost across all regions

Though we are not aware of any significant LIB manufacturing in Mexico, we include a *Mexico* scenario for purposes of comparison because it is geographically close to U.S. markets and because its labor rates are lower than the United States and approximately equivalent to labor rates in China. This scenario is intended to represent not only the potential competitiveness of Mexican production, but also what might be possible if any country were able to reproduce the combination of advantages (low labor and capital costs) modeled in that scenario.

Modeled Minimum Sustainable Price

Prices shown are modeled MSPs, which are the minimum prices a manufacturer must charge in order to earn a return equal to their cost of capital. Actual market pricing is also influenced by firm specific strategies and market conditions. Although the overall modeled cost structure for a possible Mexican LIB plant is slightly higher than that for *China Tier 1* and *Korea* scenarios, the sustainable pricing achievable in the *Mexico* scenario is the lowest of all scenarios, as shown in Figure 5.

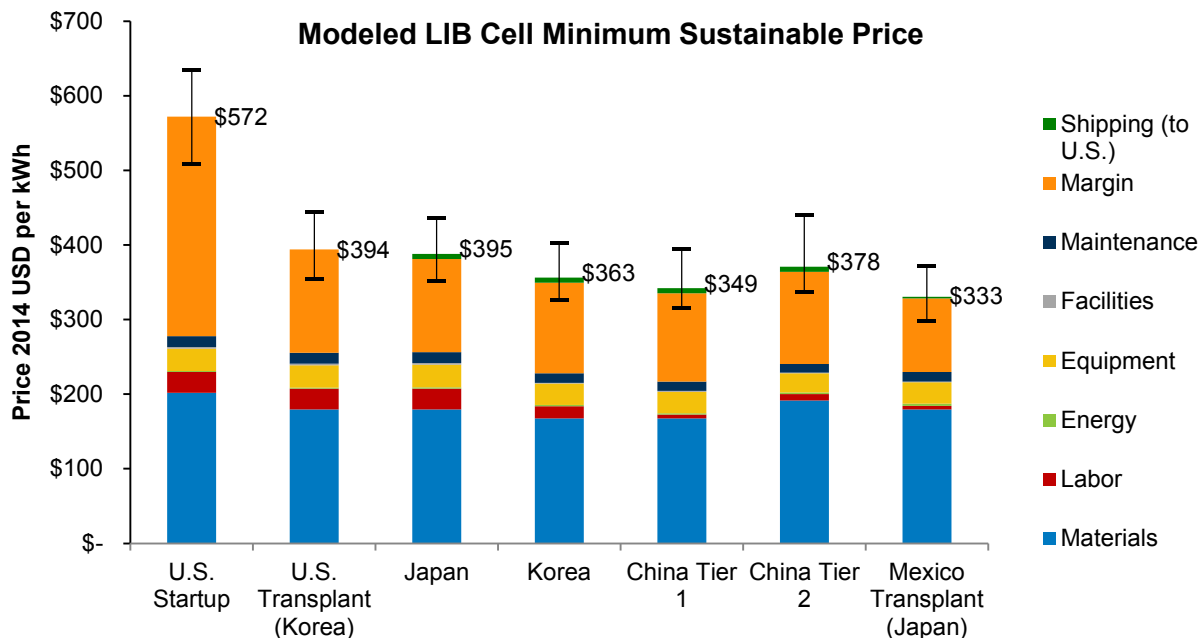


Figure 7. Modeled MSP

Mexico’s lowest sustainable price is driven by a combination of a competitive total cost structure and a low WACC due to the assumption of a Japanese parent company. The *China Tier 1* and *Korea* scenarios constitute the next lowest tier of sustainable prices, with modeled prices being within ~3% of each other. This is an unsurprising result, given that companies from these regions currently dominate LIB cell markets, along with Japanese firms. The U.S. scenarios lag behind the other scenarios due to slightly higher costs for materials, labor, and facilities, and U.S. manufacturers also require relatively high returns. The *U.S. Startup* scenario in particular reflects the difficulty of competing with a ~14% cost of capital and corresponding high margin requirements.³

Considerations for U.S.-Based Manufacturing

While the prices for the U.S. representative scenarios modeled are higher than for other modeled scenarios, U.S. pricing could possibly be competitive with current minimum sustainable pricing from low-cost producer nations such as Korea and China.⁴ We use our model to demonstrate that this could be achieved if material costs are equalized with the *Korea* and *China Tier 1* representative scenarios (which benefit both for volume and local materials discounts) and an 8% cost of capital is assumed. While equalizing material costs might require an established domestic supply chain, the cost of capital assumption appears possible even today. Using two established U.S.-based battery manufacturers (Johnson Controls and

³ The cost of capital for this scenario was developed using actual financial data from U.S. automotive battery startup company A123 when it was an independent, publicly traded firm.

⁴ By ‘competitive’, we assume pricing within 5% of representative price leaders (in this case, China Tier 1).

Energizer) as comparables suggests that an average WACC of 8.3% appears to be possible for U.S. companies engaged in the battery sector.

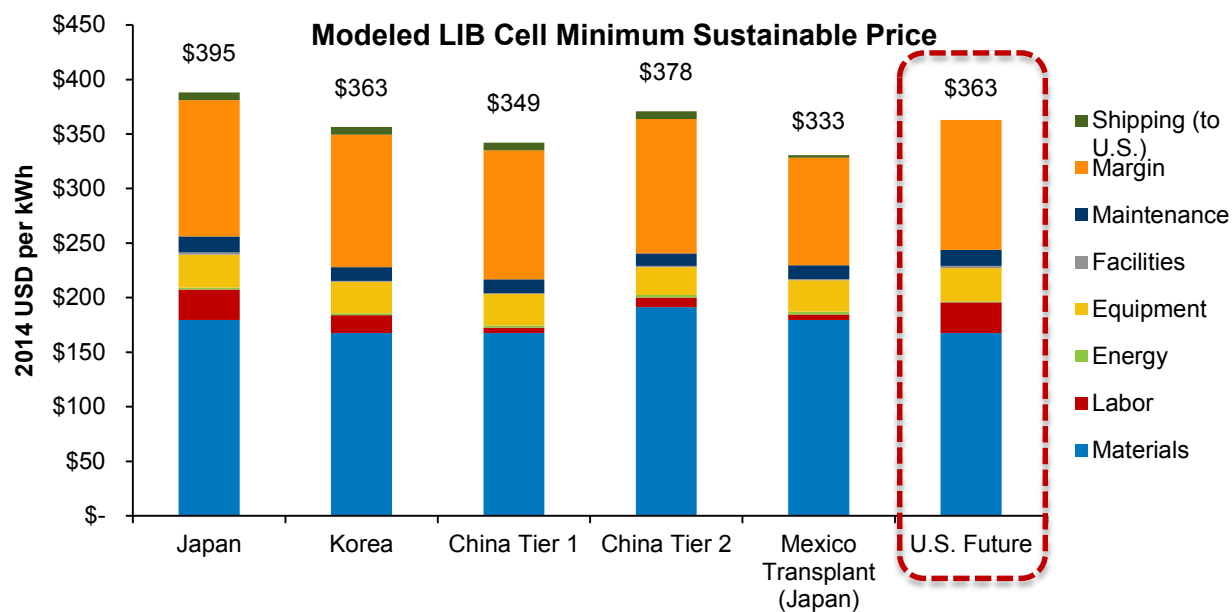


Figure 8. Modeled minimum sustainable price, U.S. Future scenario

Moreover, indirect cost and qualitative factors not captured in this model could incentivize U.S.-based LIB manufacturing, including the following (Porter and Rivkin 2012; World Bank 2013):

- Policy and regulatory contexts
- Ease-of-doing-business considerations
- Logistical risks and proximity to end markets
- Protection of intellectual property, including process innovations
- Supply chain optimization (may include vertical integration)
- Brand and reputation
- Access to talented workforce, especially to advance RD&D.

The growth of the electric vehicle market creates opportunity for U.S.-based manufacturers to capture a portion of the automotive LIB market. If xEV production continues in the United States, manufacturers may find opportunity to compete in automotive LIB production. Nonetheless, U.S.-based manufacturing faces difficult challenges given its disadvantages in various cost categories and the current relative immaturity of the U.S. supply chain and market participants.

Other Cost and Price Drivers

Yield and Utilization

Although yield and utilization were kept constant in the model (with the exception of China Tier 2), actual utilizations and yields likely vary significantly among firms, even among those within the same country. The impacts of yield and utilization on the MSP are shown in Figure 9.

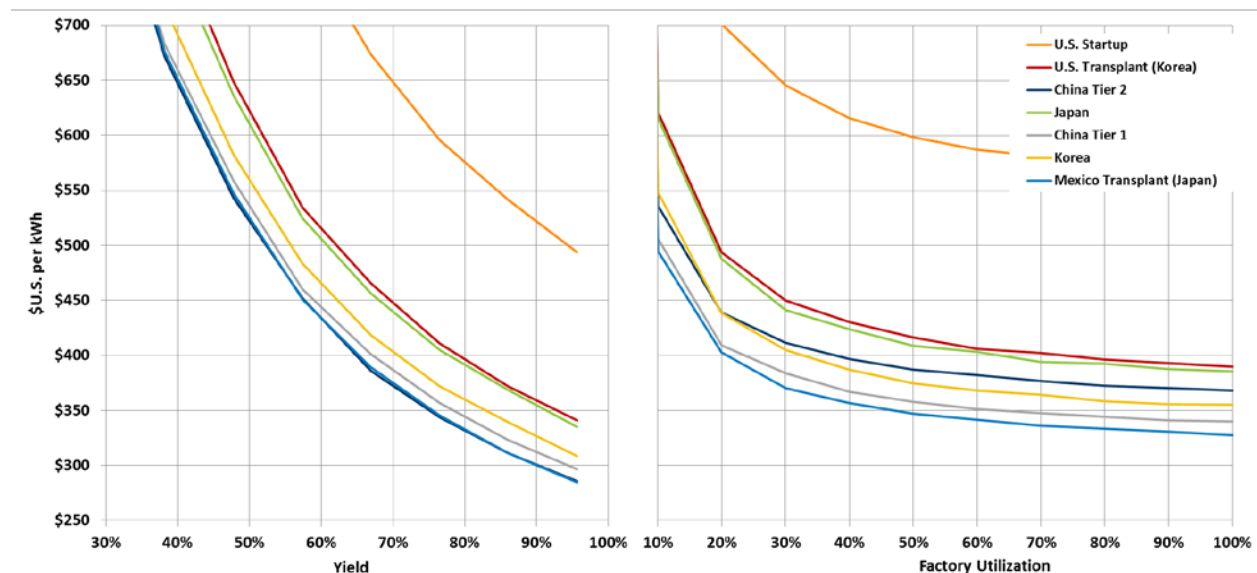


Figure 9. Modeled cell price vs. yield and utilization

Yields are likely a function of cumulative production experience in small and large format LIB cell production. NREL interviews suggest that large format LIB cell yields range between 70%–90%. This range can be attributed to the difficulty associated with precisely and consistently controlling the electrochemical reactions utilized in the battery manufacturing process. The range is also due in part to the relative immaturity of the industry itself (specifically in producing large format cells), and the diversity of experience levels various competitors possess. Incumbent firms likely achieve the higher end of this range or greater due to their experience gained from LIB production for consumer electronics applications, although large format cells can present some unique challenges. Higher yields are one way Japanese firms with relatively high cost structures may be able to compete effectively against rivals from Korea and China, who generally enjoy lower cost structures but may also sustain lower yields. In manufacturing, yield advantages are typically fleeting and diminish as competitors improve their yields as their cumulative production volumes increase.

Utilization today is particularly uncertain at the firm level due to overall overcapacity. While price is less sensitive to utilization than yield, utilization still has a material effect, especially at particularly low values. Global average utilization was estimated at 22% in 2014 (BNEF Desktop Portal 2014; Anderman 2013; NREL estimates), suggesting some firms were operating below this point, where the effect upon MSP is most severe.

Market Considerations

We note that actual selling prices may be driven by market factors other than manufacturing costs, especially in early stages of high-growth industries such as large format LIB cells. For example, due to the relative immaturity of large format LIBs, manufacturers may have initially rated the cells below their actual capacities in order to ensure products would meet or exceed their marketed specifications. This had the effect of increasing the marketed capacity normalized price (\$/kWh). Additionally, global overcapacity of LIB cell production may have led manufacturers to price products below MSP. The MSP modeled in this analysis is based on cost structure and financial parameters, and is intended to reflect long-term market clearing prices assuming a mature, balanced, and rational market.

Cells in the Context of Total LIB Supply Chain

Major components of the automotive LIB value chain include processed materials for electrodes and other components, cell manufacturing, and pack manufacturing. With respect to vertical integration, various manufacturers are employing different approaches. Pack design and production is typically performed by automakers themselves (AAB 2014) today. In contrast, LIB electrode materials, other processed materials, and complete sealed cells can be shipped without significant cost penalty relative to current market prices, and can often occur in locations separate from pack production. The ability to ship these goods suggests that regions and firms producing competitively priced cells, components, and processed materials can effectively serve global markets.

Conclusion

Factors driving the cost competitiveness of LIB manufacturing locations are mostly built, though some regional costs are significant and should be considered. We have discussed a wide variety of regional cost factors, including the cost of capital, labor, and policies, while built advantages include supply chain developments and competition, access to materials, and production expertise.

The majority of automotive LIB cell production is currently located in Asia, and is owned by firms with extensive experience in producing LIB cells for consumer electronics markets. Such incumbent competitors leverage significant advantages when competing in the automotive market, which include robust supply chains and leverage over suppliers, strategic partnerships and more diversified sales channels, higher yields, and other advantages stemming from manufacturing learning effects. However, while Asian firms currently dominate the market, price competitive production may be possible from Mexican and U.S. manufacturing locations given materials pricing equivalent to that achieved by cost leaders and an 8% WACC.

Market factors beyond incumbency, built, and regionally driven cost advantages can also affect actual observed pricing, especially during the early, relatively volatile stages of industry growth. Current automotive LIB production capacity is underutilized, affecting the unit cost of production and potentially impacting market prices and capacity investment decisions. Further, firms may be currently pursuing strategies and location decisions that only partially integrate regional cost considerations. As the automotive LIB market stabilizes and rationalizes, more straightforward cost-based pricing trends may emerge.

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Appendix

Key assumptions for the model scenarios are documented in this appendix, including key assumptions regarding country scenarios and input material costs.

Table A-1. Key Assumptions, Country Scenarios

		U.S. Startup	U.S. Transplant	Japan	Korea	Tier 1 China	Tier 2 China	Mexico
		<i>U.S.-Based New Entrant</i>	<i>Korea Owned, U.S. Factory</i>	<i>Japan Owned, Japan Factory</i>	<i>Korea Owned, Korea Factory</i>	<i>China Owned, China Factory</i>	<i>China Owned, China Factory</i>	<i>Japan Owned, Mexico Factory</i>
	<i>unit</i>							
Unskilled Cost of Wages ¹	<i>\$/hr</i>	\$18.73	\$18.73	\$18.55	\$10.88	\$3.34	\$3.34	\$3.34
Skilled Cost of Wages ²	<i>\$/hr</i>	\$26.95	\$26.95	\$26.70	\$15.65	\$13.41	\$13.41	\$13.41
Cost of Salary ³	<i>\$/yr</i>	\$90,365	\$90,365	\$89,529	\$52,491	\$16,112	\$16,112	\$16,112
Indirect:Direct Labor Ratio		0.35	0.35	0.35	0.35	0.35	0.35	0.35
Working Days per Year	<i>days/yr</i>	350	350	350	350	350	350	350
Working Hours per Day	<i>hrs/day</i>	24	24	24	24	24	24	24
Weighted Average Cost of Capital ⁴	<i>%</i>	14.3%	10.3%	7.0%	10.6%	11.4%	11.4%	7.2%
Price of Electricity ⁵	<i>/kWh</i>	\$0.040	\$0.040	\$0.070	\$0.070	\$0.077	\$0.077	\$0.107
Price of Natural Gas ⁶	<i>/m³</i>	\$0.00026	\$0.00026	\$0.00103	\$0.00051	\$0.00051	\$0.00051	\$0.00026
Price of Building Space ⁷	<i>/m²</i>	\$1,700	\$1,700	\$1,700	\$805	\$805	\$805	\$805
Equipment Installation Costs ⁸	<i>%-equipment</i>	12.0%	12.0%	12.0%	6.0%	6.0%	6.0%	6.0%
Equipment Discount ⁹	<i>%-equipment</i>	0.0%	0.0%	0.0%	0.0%	0.0%	35.0%	0.0%
Corporate Tax Rate ¹⁰	<i>%</i>	40.0%	40.0%	35.6%	24.2%	25.0%	25.0%	30.0%
SG&A ¹¹	<i>%-revenues</i>	12.3%	12.3%	12.3%	12.3%	12.3%	12.3%	12.3%
R&D ¹²	<i>%-revenues</i>	20.0%	3.5%	3.5%	3.5%	3.5%	1.8%	3.5%
Expected inflation ¹³	<i>%</i>	2.0%	2.0%	1.9%	2.7%	2.9%	2.9%	3.7%
Total Yield ¹⁴	<i>%</i>	80%	80%	80%	80%	80%	70%	80%
Automation		Yes	yes	yes	yes	yes	no	yes
Electrode line speed	<i>m/min</i>	20	20	20	20	20	10	20

¹ Bureau of Labor Statistics, 51-9198 Helpers-Production Workers, <http://www.bls.gov/OES/current/oes519198.htm#ind>

² Bureau of Labor Statistics, 51-9141 Semiconductor Processors, <http://www.bls.gov/oes/current/oes519141.htm>

³ Bureau of Labor Statistics, 51-1011 First-Line Supervisors of Production and Operating Workers, <http://www.bls.gov/oes/current/oes511011.htm>

Note: International Labor rates adjusted by international manufacturing labor rates, <http://www.bls.gov/fls/ichcc.pdf>

⁴ Public financial data accessed from Bloomberg Terminal for the following companies: Wanxiang Qianchao, BYD Co Ltd, Panasonic, Hitachi, NEC Corp, Toshiba, Samsung SDI, LG Chem, SK Innovation, Johnson Controls, Energizer; accessed December 2014

⁵ Energy Information Agency, Washington state for industrial customers, <http://www.eia.gov/electricity/data.cfm#sales>; Korea – Bloomberg, <http://www.bloomberg.com/news/2013-01-09/south-korea-increases-power-prices-second-time-to-curb-demand.html>; China: Bloomberg, <http://www.bloomberg.com/news/2011-05-30/china-raises-industrial-power-prices-in-15-provinces-to-help-ease-shortage.html>; Mexico – Secretaria De Energia, <http://www.sener.gob.mx/portal/Mobil.aspx?id=1606>

⁶ Energy Information Agency, <http://www.eia.gov/todayinenergy/detail.cfm?id=3310>

⁷ Brodd 2012

⁸ CEMAC estimate

⁹ CEMAC estimate assuming less automated, lower throughput equipment

¹⁰ Tax rates from KPMG, <http://www.kpmg.com/global/en/services/tax/tax-tools-and-resources/pages/corporate-tax-rates-table.aspx>

¹¹ Public financial data accessed from Bloomberg Terminal for the following companies: Wanxiang Qianchao, BYD Co Ltd, Panasonic, Hitachi, NEC Corp, Toshiba, Samsung SDI, LG Chem, SK Innovation, Johnson Controls, Energizer; accessed December 2014

¹² Public financial data accessed from Bloomberg Terminal for the following companies: Wanxiang Qianchao, BYD Co Ltd, Panasonic, Hitachi, NEC Corp, Toshiba, Samsung SDI, LG Chem, SK Innovation, Johnson Controls, Energizer; accessed December 2014

¹³ PriceWaterhouseCoopers, <http://www.pwc.com/gx/en/issues/economy/global-economy-watch/projections/june-2014.jhtml>.

¹⁴ Confidential conversation with industry.

Table A-2. Key Assumptions, Materials Costs

			U.S. Startup	U.S. Transplant	Japan	Korea	Tier 1 China	Tier 2 China	Mexico
Part	Description	unit	U.S.-Based New Entrant ⁴	Korea Owned, U.S. Factory	Japan Owned, Japan Factory	Korea Owned, Korea Factory	China Owned, China Factory	China Owned, China Factory	Japan Owned, Mexico Factory
Anode active material	Natural graphite (carbon coated)	USD/kg	\$14.87	\$14.87	\$ 14.87	\$13.09 ¹	\$13.09 ¹	\$13.09 ¹	\$ 14.87
	Synthetic graphite	USD/kg	\$18.00	\$18.00	\$18.00	\$15.84 ¹	\$15.84 ¹	\$15.84 ¹	\$18.00
Binder	SBR (5.0 wgt-%)	USD/kg	\$6.00	\$5.52 ²	\$5.52 ²	\$5.52 ²	\$5.52 ²	\$5.52 ²	\$5.52 ²
Solvent	Water (96 wgt-% of slurry mix)	USD/kg	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Current collector	12 um Rolled Copper	USD/m ²	\$1.80	\$1.66 ²	\$1.66 ²	\$1.66 ²	\$1.66 ²	\$1.66 ²	\$1.66 ²
Cathode active material	NMC333-G (89 wgt-%)	USD/kg	\$30.00	\$24.00 ³	\$24.00 ³	\$20.10 ³	\$20.10 ³	\$18.00 ³	\$24.00 ³
Conductive materials	Carbon black (6 wgt-%)	USD/kg	\$7.50	\$6.90 ²	\$6.90 ²	\$6.90 ²	\$6.90 ²	\$6.90 ²	\$6.90 ²
Binder	PVDF (5 wgt-%)	USD/kg	\$30.00	\$27.60 ²	\$27.60 ²	\$27.60 ²	\$27.60 ²	\$27.60 ²	\$27.60 ²
Solvent	NMP (96 wgt-% of slurry mix)	USD/kg	\$18.00	\$16.56 ²	\$16.56 ²	\$14.40 ^{1,2}	\$14.40 ^{1,2}	\$14.40 ^{1,2}	\$16.56 ²
Current collector	20 um Aluminum	USD/m ²	\$0.80	\$0.74 ²	\$0.74 ²	\$0.74 ²	\$0.74 ²	\$0.74 ²	\$0.74 ²
Separator	20 um PP (uncoated)	USD/m ²	\$2.00	\$1.84 ²	\$1.84 ²	\$1.84 ²	\$1.84 ²	\$1.84 ²	\$1.84 ²
	20 um PVDF based	USD/m ²	\$5.00	\$4.60 ²	\$4.60 ²	\$4.60 ²	\$4.60 ²	\$4.60 ²	\$4.60 ²
Electrolyte	EC/DMC/MEC-LiPF ₆	USD/kg	\$19.57	\$18.00 ²	\$18.00 ²	\$18.00 ²	\$18.00 ²	\$18.00 ²	\$18.00 ²

¹ Local production cost discount from cluster effects and policy interventions – 12% for all regions where applied

² Volume discount – 8% for all regions where applied

³ NMC discounts driven by volume purchasing, and from cluster effects and policy interventions – 20% for U.S. Transplant, Japan, and Mexico; 33% for Korea and China Tier 1; 40% for China Tier 2

⁴ Base cost from ANL's BatPak, <http://www.cse.anl.gov/batpac/>.